

Full 3+1D simulation of high energy post-compression in solid thin plates

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Abstract: A novel 3+1D numerical simulation code was developed for high-energy post-compression of ultrashort laser pulses in solid thin plates to the few-to-single-cycle temporal regime with a special emphasis on the investigation of spatio-temporal pulse distortions. © 2022 The Author(s)

1. Introduction

Laser systems nowadays are able to generate ultrashort pulses with tens of mJ and sub-15 fs duration [0]. There is a huge demand on pulses with octave spanning bandwidth and similar pulse energy. Efficient post-compression of linearly polarized pulses down to single-cycle duration was demonstrated by spectral broadening through a sequence of multiple thin plates [1-3], where the intensity at the nonlinear medium typically reaches 5-10 TW/cm². The key of this technique is the controlled utilization of periodic self-focusing and diffraction, while the nonlinear medium is kept thin enough not to introduce filamentation and significant dispersion. This technique was utilized with both Yb- and Ti:Sa-based laser systems, consequently within the input pulse duration range of 200 fs and 25 fs [4,5]. Extending the method to the multi-10 mJ regime requires significant efforts regarding the necessary vacuum environment and spatial beam characteristics.

Understanding of the key physical processes in post-compression requires advanced simulation techniques, which provide a possibility to optimize the experimental arrangements after validation with measured data. Development of a 3+1D and a 1+1D numerical code for multipass cells already provided accurate predictions on the spectrum and beam profile of the output pulses from these setups driven mainly by Yb-based laser systems [6,7]. These models are also quite useful for numerical simulation codes of further experimental arrangements.

2. Simulation code and validation

The simulation uses the split-step Fourier method [6], which performs the nonlinear and linear optical propagation steps sequentially. The nonlinear step is solved in the time domain, where the slowly evolving wave approximation is utilized. This way, self-phase modulation, self-steepening and self-focusing are inherently taken into account. During the linear step, material dispersion and linear diffraction are calculated in the frequency domain. This method is now well established [6-8], but it is often restricted to 1+1D simulations. In case of 3+1D simulations, the computational costs are limiting the application possibilities.

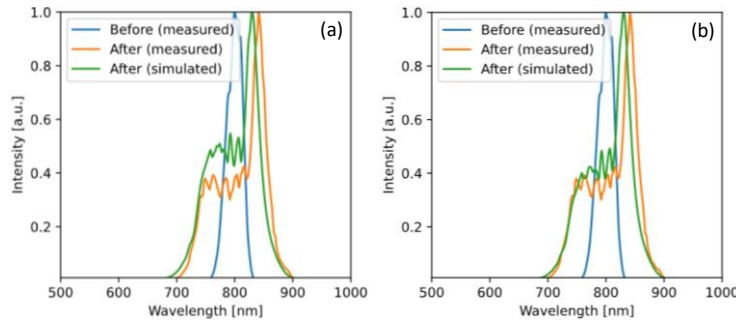


Fig. 1. Near field on-axis (a) and far field on-axis (b) intensity spectrum after one thin plate. Measured data are taken from [5].

Our simulation solves this problem by utilizing an advanced Fourier-transform technique in the spatial domain, which factorizes the large second order derivative of the phase-shift rising in propagation, thus significantly reduces its memory requirement [9]. This enables the calculation of large distance propagation of ultrashort pulses and therefore makes it possible to study the arising spatio-temporal couplings. Our 3+1D numerical code was validated by comparing it with experimental results presented in Ref. [5]. Figure 1 shows the spectral evolution of the pulse in the

first and second thin plate compressor stages of Ref. [5]. The results of our 3+1D simulation match very well the experimental results, providing a better understanding of the underlying processes than the 1+1D presented in [5].

3. Results and conclusions

Capabilities of the simulation code were tested by investigating the post-compression of a high peak power laser system. For this, we needed input data from a well characterized laser system, which was chosen to be the SYLOS Experimental Alignment (SEA) laser of ELI-ALPS. Input pulses of 30 mJ energy, 12 fs pulse duration and 64 mm near field spatial profile were taken. All input data were based on measured values, namely the measured spectral amplitude and phase, near field spatial profile were utilized without any fitting on them.

The simulated optical arrangement is composed of a sequence of thin plates with 150 μm thickness. The spectral broadening process is obtained close to the image plane of the focusing elements, thus the plates are positioned effectively in the near field, which is visible in Fig. 2(a). The spectral broadening is visualized in the 2D spectrum integrated over one transversal coordinate is shown in Fig. 2(b) after the first plate.

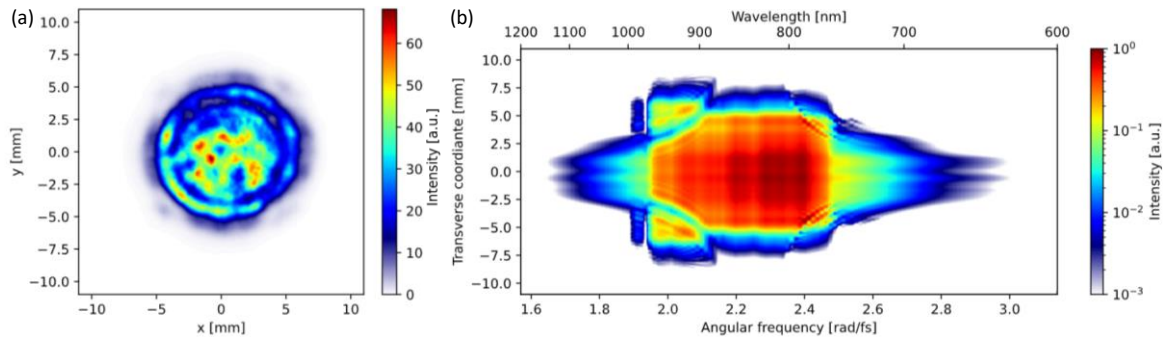


Fig. 2. Near field intensity profile (left panel) and 2D output axial spectrum (right panel) of the output pulse after one thin plate.

Opposite to the already published implementation of the multiple thin plate method, in our setup the spectral broadening process takes place in the image planes, where the near field is re-imaged every time from each thin plate.

In conclusion, we developed a novel numerical simulation code for the investigation of post-compression in solid thin plates. The code was validated with the use of experimental data from the literature. Taking advantage of the advanced spatial Fourier-transform algorithm, we were able to simulate linear and nonlinear propagation in a post-compression setup with tens of mJ energy input pulses. We think that the advancements implemented in our code are providing the possibility for Joule level post-compression to be examined numerically in 3+1D. Furthermore, utilization of the code in petawatt level post-compression simulations could give a better insight to the experimental results like in case of Ref. [11] and lead to significant optimization of such systems.

4. References

- [1] Sz. Toth et al., "SYLOS lasers – the frontier of few-cycle, multi-TW, kHz lasers for ultrafast applications at extreme light infrastructure attosecond light pulse source" *J. Phys. Photonics* 2 (2020) 045003
- [2] C.-H. Lu, Y.-J. Tsou et al., "Generation of intense supercontinuum in condensed media," *Optica* 1, 400-406 (2014).
- [3] Y.-C. Cheng, C.-H. Lu, Y.-Y. Lin et al., "Supercontinuum generation in a multi-plate medium," *Opt Express* 24, 7224–7231 (2016).
- [4] He P, Liu Y, Zhao K et al, "High-efficiency supercontinuum generation in solid thin plates at 0.1TW level," *Opt Lett*. 42, 474–477 (2017).
- [5] C.-H. Lu, W.-H. Wu, S.-H. Kuo, J.-Y. Guo, M.-C. Chen, S.-D. Yang, and A. H. Kung, "Greater than 50 times compression of 1030 nm Yb:KGW laser pulses to single-cycle duration," *Opt. Express* 27, 15638-15648 (2019).
- [6] M. Stanfield, N. F. Beier, S. Hakimi, H. Allison, D. Farinella, A. E. Hussein, T. Tajima, and F. Dollar, "Millijoule few-cycle pulses from staged compression for strong and high field science," *Opt. Express* 29, 9123-9136 (2021).
- [7] M. Hanna, X. Délen, L. Lavenue, F. Guichard, Y. Zauoter, F. Druon, and P. Georges, "Nonlinear temporal compression in multipass cells: theory," *J. Opt. Soc. Am. B* 34, 1340-1347 (2017).
- [8] N. Daher, F. Guichard, S. W. Jolly, X. Délen, F. Quéré, M. Hanna, and P. Georges, "Multipass cells: 1D numerical model and investigation of spatio-spectral couplings at high nonlinearity," *J. Opt. Soc. Am. B* 37, 993-999 (2020).
- [9] G. Ycas, D. Maser, and D. Hickstein, "Pynlo: Nonlinear optics modelling for python", <https://pynlo.readthedocs.io/en/latest/> (2015).
- [10] Sz. Tóth, "Optimization of high peak power few-cycle optical parametric chirped pulse amplifier systems" PhD thesis, University of Szeged, (2021).
- [11] V. Ginzburg, I. Yakovlev, A. Kochetkov, A. Kuzmin, S. Mironov, I. Shaikin, A. Shaykin, and E. Khazanov, "11 fs, 1.5 PW laser with nonlinear pulse compression," *Opt. Express* 29, 28297-28306 (2021)